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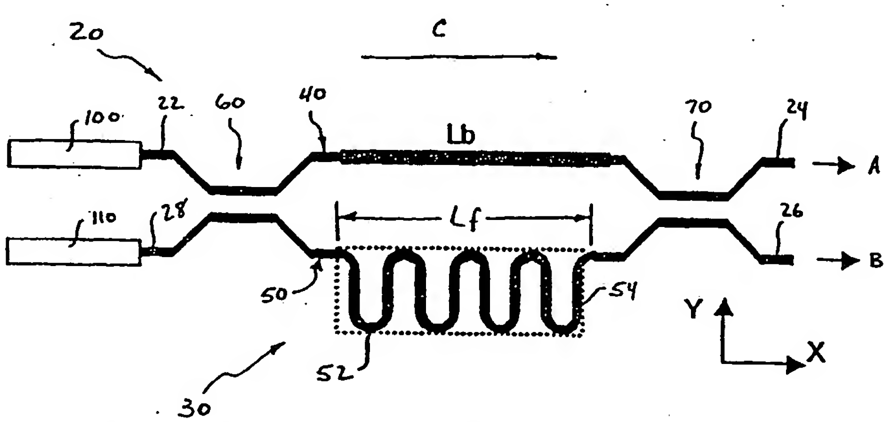
(54) Title: A NANOPHOTONIC MACH-ZEHNDER INTERFEROMETER SWITCH AND FILTER



(57) Abstract: A nanophotonic Mach-Zehnder interferometer (MZI) device having at least one arm which has an actual length greater than its virtual length. An arcuate section is provided in at least one arm (thus providing a "meandering arm") to increase the actual length of that arm without increasing its virtual length and without compromising the ability of that arm to effect a π phase shift in an optical signal propagating therein. By constructing the MZI device of strongly confined waveguides, which may be either photonic-well or photonic-wire devices, the low bending loss characteristics of such waveguides enable the use of an arcuate section or bend in the waveguide without experiencing undesirable losses in the optical signal. The actual length of the arm and the optical length are equivalent to those for prior art devices and sufficient to introduce the desired phase shift. In contrast to prior art devices, however, the present invention provides those sufficient actual and optical lengths in a significantly reduced length on the chip (i.e., its virtual length) that requires less on-chip real estate and thus provides for denser integration of a plurality of optical devices in an optical component.

WO 01/23955 A2

A NANOPHOTONIC MACH-ZEHNDER INTERFEROMETER SWITCH AND FILTER

FIELD OF THE INVENTION

The present invention is directed to nanophotonic Mach-Zehnder interferometer (MZI) devices and structures.

BACKGROUND OF THE INVENTION

An optical network, in its simplest representation, consists of an optical source, a destination, and a matrix of devices (e.g., fiber-optical cables, waveguides, cross-connects, amplifiers, etc.) for causing an optical signal generated by the source to reach a desired destination. Physical and geographic boundaries present no impediment to telecommunication, data communication and computing, all of which may utilize all or part of an optical network. Consequently, the number or sources and destinations, and the combinations of sources and destinations and the communication paths therebetween, may be nearly infinite. Optical switches provide obviously necessary devices in the optical network for facilitating the routing of an optical signal to its desired destination.

The ability to distinguish one optical signal from a plurality of optical signals (or one wavelenght from a plurality of wavelengths in an optical signal) propagating within an optical network is critical as the number of signals transmitted through a single optical fiber (or waveguide) increases. As optical transmission evolves from wave-division-multiplexing (WDM), to dense WDM (DWDM), to ultra-dense wave-division-multiplexing (UDWDM), and beyond, more and more data in the form of a multi-wavelength optical signal is transmitted over the optical network. Optical filters comprise one component that may be used to pluck a desired signal (i.e., a desired wavelength) at a particular point or location in

the network and route that desired signal to its desired destination, while also permitting undesired signals to continue along the network.

Size is also an important factor in the construction of optical components capable of satisfying the demands of current and future optical networks and communications. High-density integration of optical components requires that the multiple optical devices, interconnects, interfaces, etc., that make up an optical component all occupy a minimal amount of real estate. As is the case with electronic integrated circuits, it is desirable to pack as many optical devices in an optical component as possible (an analogous comparison is the number of transistors provided in an integrated circuit). Current optical switches may be constructed using a directional coupler or a Mach-Zehnder interferometer (MZI). In each case, the conditions for effecting optical switching, which occurs by introducing a π phase shift into at least a part of the optical signal, are defined by the equation:

$$\Delta\phi = \pi = \frac{2\pi}{\lambda}\Delta nL \tag{1}$$

where $\Delta\phi$ is the desired phase shift, λ is the wavelength of the optical signal propagating in the device, L is the actual length of the device, and Δn is the change in refractive index effected by the application of a carrier signal or electrical field to the device. Since the change in refractive index typically achievable for current optical devices is on the order of approximately 10^{-3}, the actual length of the device needed to introduce a π phase shift must be at least 1 mm, and preferably longer. However, to achieve large-scale density integration, the actual length L must be reduced without sacrificing the ability to effect a π phase shift in an optical signal. Those two requirements are in opposite each other.

There thus exists a need in the art for an optical device that overcomes the above-described shortcomings of the prior art.

SUMMARY OF THE INVENTION

The present invention combines the strong photon confinement characteristics of nanophotonic waveguides and the functionality of a Mach-Zehnder interferometer (MZI) to provide a compact optical device suitable for large-scale (i.e., dense) integration. The MZI is constructed in essentially the same manner as a conventional MZI: including two 3 dB couplers joined by two interferometer arms, one of which may have an electrical contact that enables electrical control of the refractive index of that arm. In one embodiment of the present invention, both of the arms include an arcuate section that enable construction of an MZI having arms with respective virtual lengths that are less than their respective actual lengths. In an alternate embodiment, only one of the interferometer arms may include an arcuate section, thus providing a built-in phase difference between the two arms, rather then the previously described electrically controllable phase difference. The couplers may be co-directional, Y-branches or multi-mode interferometer (MMI) couplers, as a matter of design choice.

The present invention is directed to a nanophotonic Mach-Zehnder interferometer device that includes at least one interferometer arm having an arcuate section that reduces the amount of real estate occupied by that arm without compromising the ability of that arm to effect a π phase shift in an optical signal propagating therein. The arcuate section enables the length in one direction of the arm to be reduced, yet ensures that the optical length of that arm is sufficient to induce the desired phase shift in an optical signal propagating therethrough. By constructing the device of strongly confined waveguides, which may be either photonic-well or photonic-wire devices, the low bending loss characteristics of such waveguides enable the use of an arcuate section or bend in the waveguide without experiencing undesirable

losses in the optical signal. Typically, optical waveguides must be substantially straight to minimize losses in the optical signal. The present invention advantageously utilizes the improved optical characteristics of strongly confined waveguides (e.g., the ability to propagate light through a curve with low optical loss) to enable the use of curved waveguides in a Mach-Zehnder interferometer arm. Thus, the interferometer arm may be constructed as a number of "S" shaped sections so as to "meander" over its actual length.

In an embodiment of the present invention, a nanophotonic Mach-Zehnder interferometer has first and second arms having respective first and second actual lengths and respective first and second virtual lengths extending along an optical path direction of the interferometer. The actual length of one of the interferometer arms is greater than its virtual length. An optical signal propagating through that arm will experience a phase shift when compared with an optical signal propagating through the other arm.

In another embodiment of the present invention, a nanophotonic Mach-Zehnder interferometer has first and second arms of having respective first and second actual lengths and respective first and second virtual lengths extending along an optical path direction of the interferometer. The actual lengths of the first and second arms are each greater than their respective virtual lengths. The interferometer also includes an electrical contact coupled to one of the interferometer arms. An electrical signal selectively applied to the interferometer arm via the electrical contact can cause the optical length of that arm to change. Consequently, an optical signal propagating through that arm will experience a phase shift when compared with an optical signal propagating through the other arm.

In yet another embodiment of the present invention, a nanophotonic switch for receiving and switching an optical signal comprises a Mach-Zehnder interferometer having an input coupler for receiving an optical signal and an output coupler. First and second

interferometer arms are optically connected between the input and output couplers along an optical path of the switch. The arms have respective first and second actual lengths and respective first and second virtual lengths extending along the optical path of the switch. The actual lengths of the first and second arms are greater than their respective virtual lengths. The switch also includes an electrical contact coupled to one of the interferometer arms. An electrical signal selectively applied to the interferometer arm via the electrical contact can cause the optical length of that arm to change. Consequently, an optical signal propagating through that arm will experience a phase shift when compared with an optical signal propagating through the other arm.

In still another embodiment of the present invention, a nanophotonic filter for receiving and filtering an optical signal comprises a Mach-Zehnder interferometer having an input coupler for receiving an optical signal and an output coupler. First and second interferometer arms are optically connected between the input and output coupler along an optical path of the filter. The arms have respective first and second actual lengths and respective first and second virtual lengths extending along an optical path direction of the filter. The actual length of one of the interferometer arms is greater than its virtual length. An optical signal propagating through that arm will experience a phase shift when compared with an optical signal propagating through the other arm.

The invention accordingly comprises the features of construction, combination of elements, and arrangement of parts which will be exemplified in the disclosure herein, and the scope of the invention will be indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawing figures, which are not to scale, and which are merely illustrative, and wherein like reference characters denote similar elements throughout the several views:

FIG. 1 is a schematic block diagram of a 1 x 16 switch that is part of a high-density optical component;

FIG. 2 is a schematic diagram of a nanophotonic switch having a Mach-Zehnder interferometer constructed in accordance with the present invention;

FIG. 3 is a schematic diagram of a nanophotonic filter having a Mach-Zehnder interferometer constructed in accordance with the present invention; and

FIG. 4 is a cross-sectional view of a nanophotonic waveguide that provides strong photon confinement.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

The present invention is directed to a nanophotonic Mach-Zehnder interferometer (MZI) device having at least one arm which has an actual length greater than its virtual length. An arcuate section is provided in at least one arm to increase the actual length of that arm without increasing its virtual length. As used herein, the term "virtual length" refers to the length of an interferometer arm in one direction; preferably, in a direction coaxial to and extending along an optical path direction of the interferometer. The present invention enables the construction of significantly smaller nanophotonic device than typical photonic devices, and significantly reduces the amount of on-chip real estate occupied by such devices, while not affecting the ability of such devices to introduce a predetermined phase shift in an optical signal.

The present invention takes advantage of the low bending loss properties of strongly confined nanophotonic waveguides to provide a bend or arcuate section in the MZI arm. The actual length of the arm and the optical length (e.g., actual length times refractive index *n*) are equivalent to those for prior art devices and sufficient to introduce the desired phase shift. In contrast to prior art devices, however, the present invention provides those sufficient actual and optical lengths in a significantly reduced length on the chip (i.e., its virtual length) that requires less on-chip real estate and thus provides for denser integration of a plurality of optical devices in an optical component. The strong photon confinement properties of nanophotonic waveguides, such as are disclosed in U.S. Patent Numbers 5,878,070 and 5,790,583, facilitate construction of optical devices that provide the benefits and advantages of the present invention.

Referring now to the drawings in detail, FIG. 1 depicts a block diagram of a part of an optical component 10 comprising a plurality of optically interconnected optical devices 20 (e.g., switches, filters, etc.). As used herein, the terms "optical component" and "component" refer to a plurality of interconnected devices which may be any combination of optical, opto-electrical, and/or electrical and which may be constructed as an integrated circuit. Various other optical, opto-electrical, and/or electrical devices may also be included in the optical component, as a matter of design choice. As used herein, the terms "optical", "opto-electrical", and "electrical" devices may include, by way of non-limiting example, lasers, waveguides, couplers, switches, filters, resonators, interferometers, amplifiers, modulators, multiplexers, cross-connects, routers, phase shifters, splitters, fiber-optic cables, and various other optical, opto-electrical, and electrical devices. The devices 20 depicted in FIG. 1 are merely illustrative of an embodiment of the present invention.

Referring next to FIG. 2, an optical switch 20 having two branches 200, 300 and constructed in accordance with an embodiment of the present invention is depicted. The switch 20 includes a Mach-Zehnder interferometer 30 having first and second arms 40, 50 optically coupled between an input coupler 60 and an output coupler 70 along an optical path direction of the switch 20; the optical path direction representing the direction of light propagation through the switch 20 and being indicated in the figure by arrow C. The couplers 60, 70 depicted in FIG. 2 are co-directional, 3 dB couplers. Alternatively, Y-branches or multi-mode interferometer (MMI) couplers may be provided, as a routine matter of design choice.

The switch 20 may receive an optical signal input from either one of two optical sources 100, 110 which may comprise a laser, fiber-optic cable, or other up-stream (along the optical path direction) light generating or light propagating device or system. A first optical signal may be directed into an input 22 of the switch 20 by first optical source 100. The first optical signal may comprise a single- or multi-wavelength signal, and may be selectively switched to either output A or B. Similarly, and alternatively, a second optical signal may be directed into an input 28 by a second optical source 110, and may also be selectively switched to either of output A or B. Outputs 24, 26 are sine and cosine functions of wavelength, respectively (as described in more detail below), and thus complementary.

Each branch 200, 300 of the switch 20 depicted in FIG. 2 is constructed as a nanophotonic waveguide, as described in more detail below. The term waveguide, as used herein, refers generally to a photonic-well or photonic-wire structure that provides strong photon confinement. The term waveguide is not intended as a limitation on the construction, shape, materials, functionality, or any other aspect of the optical device 20 and component 10 of the present invention, but merely as a general reference.

With continued reference to FIG. 2, the optical signal passes through an input coupler 60 which functions as a 50:50 splitter to direct approximately one-half (in terms of signal amplitude or power) of the input optical signal to each of the first and second arms 40, 50 of the MZI 30. The split optical signal passes through each of the first and second arms 40, 50, and is recombined by an output coupler 70 and output from either output A or B, depending on the phase shift introduced by the MZI 30. The two outputs 24, 26 of the switch 20 are complementary and respectively provide an optical signal of the form $P_A = \sin^2(\Delta\phi/2)$ and $P_B = \cos^2(\Delta\phi/2)$.

Each of the first and second arms 40, 50 define an actual length which is defined as the end-to-end waveguide length of each arm 40, 50. The actual length may be measured, for example, by fully extending each arm to form a straight waveguide and measuring the length of the straightened waveguide. Each of the first and second arms 40, 50 also defines a respective virtual length, designated as L_f in the figures, and generally defined as the length of the arms 40, 50 in the optical path direction of the respective interferometer arm 40, 50. Minimizing the virtual length L_f of the arms 40, 50 of the MZI 30 permits a greater number of optical devices 20 constructed in accordance with the present invention to be provided in a single optical component 10.

In preferred embodiments of the present invention, the actual length of at least one interferometer arm is greater than its respective virtual length. This is preferably accomplished by providing an arcuate section 42, 52 and a straight section 44, 54 in the respective interferometer arm 40, 50 to permit a longer interferometer arm (i.e., longer actual length) to be constructed using less on-chip real estate. Depending on the radius of the arcuate section 42, 52, the actual length may range from approximately 1 mm to approximately 2 mm, while the virtual length L_f may be smaller and may facilitate

construction of a MZI 30 having interferometer arms that may be between 10 and 40 times smaller than a conventional MZI with straight arms (i.e., the reduction factor provided by the present invention). Longer straight sections 44, 54 may be provided in accordance with the present invention to increase the actual length without a corresponding increase in virtual length and thus provide an increased reduction factor.

The use of InP-based nanophotonic waveguides in the construction of the MZI 30 enable a significant increase in the bend radius of the arcuate section 42, 52 without an increase in optical signal loss due to propagation of light through a bend or curved section of a waveguide. For an InP-based waveguide, the arcuate section 42, 52 may have a bend radius ranging from approximately 20 μm to approximately 100 μm; with a preferred bend radius of approximately 50 μm. In contrast, a bend radius of approximately 1 cm is required for Lithium Niobate waveguides, and approximately 3 mm for silica/glass waveguides. The bend radius and number of arcuate sections 42, 52 provided in each arm 40, 50 depend, at least in part, on the functional and structural requirements of the switch 20 and optical component 10. Thus, the many variations possible are contemplated by the present invention.

Notwithstanding the unique construction of the first and second arms 40, 50 provided by the present invention, the MZI 30 of the present invention functions similarly to other Mach-Zehnder devices. A phase shift of between 0° and π° may be introduced into an optical signal propagating in one interferometer arm if the optical length (the product of the actual length of that arm and its refractive index n) of that arm is different from the optical length of the other interferometer arm. Where the actual length of the two interferometer arms are approximately equal, the optical length of an interferometer arm may be changed by application of an electrical signal to that arm. The electrical signal changes the refractive index of the arm to which it is applied and thus changes the optical length of that arm. In that

manner, a phase shift determined by the applied electrical signal may be introduced into an optical signal propagating through that arm. Application of an electrical signal is typically a preferred method of changing the optical length where the actual lengths of the interferometer arms are approximately equal.

An electrical signal connected to one arm 50 of the MZI 30 may apply a drive voltage which causes the refractive index and thus optical path length of that arm 50 to change. Consequently, the optical signal propagating in that arm 50 experiences a phase shift based on the amplitude of the drive voltage. Preferably, the applied drive voltage varies so as to cause a phase shift in the optical signal propagating in that arm 50 of between approximately 0° and π°.

Alternatively, the interferometer arms may not be the same length, thereby introducing a phase shift into an optical signal propagating through one arm when compared to an optical signal propagating through the other arm, by virtue of the different actual (and thus, optical) lengths of the arms.

When constructed as either of the above-described embodiments, the present invention advantageously enables construction of interferometer arms having actual lengths that are greater than their respective virtual lengths, resulting in construction of smaller, more densely packaged optical components and optical, opto-electrical, and/or electrical devices.

With continued reference to FIG. 2, an electrical signal may be coupled to an interferometer arm 50 via an electrical contact 80. As described above, the electrical signal causes a change in the refractive index of that arm 50 which changes the optical length of that arm and causes an optical signal propagating in that arm to effectively experience a longer optical path. Consequently, a phase shift is introduced in that signal. The phase shifted optical signal (propagating through branch 300 and arm 50) combines with the non-phase

shifted optical signal (propagating through branch 200 and arm 40) via the output coupler 70. Depending on the relative phase shift between the two arms of the interferometer, the optical signal may be switched between the two output ports 24, 26 of the switch 20.

With reference next to FIG. 3, a filter 20 including a MZI 30 constructed in accordance with the present invention is depicted. The two arms 40, 50 of the MZI 30 have a built-in phase difference due to the different actual lengths of the arms. The first arm 40 is a substantially straight waveguide, while the second arm 50 includes both an arcuate section 52 and a straight section 54 that increases the actual length of that arm. When combined via the output coupler 70, the optical signals propagating in the first and second arms 40, 50 (which was split by the input coupler 60) will be out of phase with each other due to the different actual lengths of the arms 40, 50, with only a predetermined wavelength propagating out of the filter 20; that predetermined wavelength being determined by the amount of phase shift introduced via the second arm 50. In this embodiment, no external electrical source is required, nor is it necessary to change the refractive index of either arm. The built-in phase difference of the filter 20 of FIG. 3 is defined by the equation:

$$\Delta\phi = \frac{2\pi}{\lambda} n_{eff}(L - L_b) \tag{2}$$

where n_{eff} is the effective refractive index of the waveguide of the second interferometer arm 50, L is the actual length of that arm 50, and L_b is the actual length of arms 40.

For various values of λ, the phase shift given by Eq. 2 equates to an integer multiple of π. At these λ values, the optical signal at one of the output ports will be at a maximum while at the other output port will be at a minimum. The situation is reversed at those wavelengths for which the phase shift equals to a half-integer multiple of π. Thus, the signals A, B at the two outputs 24, 26 of the filter 20 are periodic functions of wavelength with a periodicity given by:

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\lambda}{n_{eff}\Delta L} \tag{3}$$

where $\Delta L = (L - L_b)$. To tune each MZI 30 over its complete periodic operating range, the differential path length (i.e., ΔL) need only be varied by a maximum of $\lambda/2$. A plurality of filters 20 constructed in accordance with the present invention and cascaded as depicted in FIG. 1 may be used to construct narrowband filters for isolating a desired wavelength. The use of nanophotonic waveguides in the construction of switches, filters, and other optical and electro-optical devices and components in accordance with the present invention permit the realization of significant differential path lengths in very small areas.

An illustrative, non-limiting cross-sectional representation of a strongly confined waveguide 110 is depicted in FIG. 4. That cross-section is representative of the cross-sectional structure of a waveguide used in the construction of the switch and filter disclosed herein and of an optical device constructed in accordance with the present invention. The waveguide is constructed on an InP substrate 112 and is comprised of a relatively high (e.g., n = 3.5) refractive index core 116 surrounded on at least two sides (in the horizontal direction in FIG. 4) by a relatively low refractive index medium 120 such as, air. The core 116 is sandwiched between upper and lower cladding layers 114, 118 that are also preferably InP material. The present invention also contemplates waveguides constructed in Lithium Niobate, silica/glass, and other semiconductor materials provided that strong confinement (at least in the horizontal direction in FIG. 4) is achieved.

With continued reference to FIG. 4, the waveguide 110 there depicted in cross-section may comprise either a photonic-well or a photonic-wire waveguide. Exemplary photonic-wire and photonic-well devices are respectively disclosed in U.S. Patent Nos. 5,878,070 and 5,790,583, the entire disclosure of those patents being incorporated herein by reference. The waveguide 110 is formed of semiconductor materials for on-chip integration with other

devices such as a semiconductor laser to construct an optical component 10 . A wafer epitaxial growth process is used to form the various semiconductor layers of the waveguide 110 on the substrate 112. As depicted in FIG. 4, a lower cladding layer 118, preferably of InP, is formed on the substrate 112, also preferably InP. A core 116 is formed on the first cladding layer 118 and may be comprised of, by way of non-limiting example, InGaAsP. An upper cladding layer 114, also preferably of InP, is formed on the core 116. The lower cladding layer 118 may be suitably doped to form n-type semiconductor material, and the upper cladding layer 114 may be suitably doped to form p-type semiconductor material, thus forming a P-I-N structure of stacked, layered semiconductor materials.

With continued reference to FIG. 4, for a photonic-well waveguide 110, the core 116 is a relatively high refractive index semiconductor material having a refractive index n_{core} greater than about 2.5, such as from about 3 to about 3.5 and above, for InGaAsP, AlGaAs, InGaN/AlGaN materials. The upper and lower cladding layers 114, 118 have a slightly lower refractive index compared to the core 116 and thus weakly confine photons within the waveguide in the vertical direction. However, strong lateral confinement is still provided by the difference between refractive index of the core 116 and the relatively low refractive index medium 120 laterally surrounding the core 116. In a photonic-well waveguide 110, the cladding layers 114, 118 may have a refractive index of about 3.17 as compared to the refractive index of 1 for air or of 1.5 for silica. The refractive index of cladding layers 114, 118 is slightly less than the refractive index of core 116, which is preferably about 3.4.

In a photonic-wire waveguide 110, the upper and lower cladding layers 114, 118 have a very low refractive index as compared to the refractive index of the core 116 and thus strongly confine photons in all directions about the waveguide core 116. Typical low refractive index mediums 120 described below for use in practicing the present invention

have refractive index n_{low} below about 2.0, preferably below 1.6, such as from about 1.5 to about 1.0. The ratio of the refractive indices n_{core}/n_{low} is preferably larger than about 1.3.

In practicing embodiments of the present invention, a waveguide 110 (photonic-well or photonic-wire) may comprise semiconductor materials such as In_xGa_{1-x}, As_yP_{1-y}, or $In_xAl_{1-x-y}Ga_yAs$ as the n_{core} and n_{high} materials and an aforementioned material with a refractive index of about 1.6 or lower as the n_{low} material. Alternately, the waveguide 110 may comprise semiconductor materials $In_xGa_{1-x}N/Al_xGa_{1-x}N$ as the n_{core} and n_{high} materials and a material with a refractive index of about 1.6 or lower as the n_{low} material. Still further, the waveguide 110 may comprise semiconductor materials $Al_xGa_{1-x}As$ or $In_xGa_{1-x}P$ as the n_{core} and n_{high} materials and a material with a refractive index of about 1.6 or lower as the n_{low} material.

For a photonic-wire waveguide device, the high refractive index semiconductor waveguide core 116 is surrounded by a relatively low refractive index medium on all sides. For a photonic-well waveguide device, the high refractive index semiconductor waveguide core 116 is surrounded by a relatively low refractive index medium on two sides opposite to each other. These constructions form strong confining potential walls for photons and confine photons tightly in all directions perpendicular to their direction of propagation through the waveguide 110. The strong potential is necessary to affect the emission properties of the active medium of the waveguide, and can be used to dramatically increase the percentage of emission into one particular waveguiding mode of interest. For example, typical semiconductor waveguide core materials for use in practicing the present invention have a refractive index n_{core} greater than about 2.5, such as from about 3 to about 3.5 and above for InGaAsP, AlGaAs, etc. materials, whereas typical low-refractive index mediums for use in practicing the invention have refractive index n_{low} below about 2.0, such as from about 1.6 to about 1.0 for silica, silicon nitride, acrylic, polyimide, aluminum oxide, epoxy,

photoresist, PMMA, spin-on glass, polymers with low absorption at the emission wavelength, or air. The ratio of the refractive indices n_{core}/n_{low} has to be larger than about 1.3, in accordance with preferred embodiment of the present invention.

The above-described semiconductor materials and relative refractive indices are illustrative, non-limiting examples of embodiments of the waveguide structure of the present invention.

Thus, while there have been shown and described and pointed out novel features of the present invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the form and details of the disclosed invention may be made by those skilled in the art without departing from the spirit of the invention. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

CLAIMS

What is claimed is:

1. A nanophotonic Mach-Zehnder interferometer comprising a first arm and a second arm having respective first and second actual lengths and respective first and second virtual lengths extending along a direction of said interferometer, one of said first and said second arms having an actual length greater than its virtual length.

2. A nanophotonic Mach-Zehnder interferometer as recited by claim 1, wherein said one of said first and said second arms includes an arcuate section that changes the actual length of that arm without changing its virtual length.

3. A nanophotonic Mach-Zehnder interferometer as recited by claim 2, wherein said arcuate section defines a bend radius ranging from approximately 20 micrometers to 100 micrometers.

4. A nanophotonic Mach-Zehnder interferometer as recited by claim 3, wherein said arcuate section defines a bend radius ranging from approximately 50 micrometers to 100 micrometers.

5. A nanophotonic Mach-Zehnder interferometer as recited by claim 1, wherein said virtual length of said first arm is approximately equal to said virtual length of said second arm.

6. A nanophotonic Mach-Zehnder interferometer as recited by claim 5, wherein said actual length of said first and said second arms ranges from approximately 1 mm to approximately 4 mm and wherein said virtual length of said one of first and said second arms ranges from approximately 100 micrometers to approximately 500 micrometers

7. A nanophotonic Mach-Zehnder interferometer as recited by claim 1, wherein each of said first and second arms have an actual length greater than said respective first and second virtual lengths.

8. A nanophotonic Mach-Zehnder interferometer as recited by claim 1, wherein said interferometer arms each comprise a photonic-well waveguide.

9. A nanophotonic Mach-Zehnder interferometer as recited by claim 1, wherein said interferometer arms each comprise a photonic-wire waveguide.

10. A nanophotonic Mach-Zehnder interferometer comprising:

a first arm and a second arm having respective first and second actual lengths and respective first and second virtual lengths extending along a direction of said interferometer, said first and said second actual lengths being greater than said respective first and second virtual lengths; and

an electrical contact coupled to one of said first and said second arms for selective application of an electrical signal to said one of said first and said second arms.

11. A nanophotonic Mach-Zehnder interferometer as recited by claim 10, wherein said first and said second arms each include an arcuate section that changes the actual length of that arm without changing its virtual length.

12. A nanophotonic Mach-Zehnder interferometer as recited by claim 11, wherein said arcuate section of said first and said second arms defines a bend radius ranging from approximately 20 micrometers to 100 micrometers.

13. A nanophotonic Mach-Zehnder interferometer as recited by claim 11, wherein said arcuate section of said first and said second arms defines a bend radius ranging from approximately 50 micrometers to 100 micrometers.

14. A nanophotonic Mach-Zehnder interferometer as recited by claim 10, wherein said virtual length of said first arm is approximately equal to said virtual length of said second arm.

15. A nanophotonic Mach-Zehnder interferometer as recited by claim 14, wherein said actual length of said first and said second arms ranges from approximately 1 mm to approximately 4 mm and wherein said virtual length of said first and said second arms ranges from approximately 100 micrometers to approximately 500 micrometers.

16. A nanophotonic Mach-Zehnder interferometer as recited by claim 10, wherein said interferometer arms each comprise a photonic-well waveguide.

17. A nanophotonic Mach-Zehnder interferometer as recited by claim 10, wherein said interferometer arms each comprise a photonic-wire waveguide.

18. A nanophotonic switch for receiving and switching an optical signal, said switch comprising:

a Mach-Zehnder interferometer comprising:

an input coupler for receiving an optical signal;

an output coupler;

first and second arms optically connected between said input and said output coupler along an optical path of said switch, said arms having respective first and second actual lengths and respective first and second virtual lengths extending along a direction of said interferometer, said first and said second actual lengths being greater than said respective first and second virtual lengths; and

an electrical contact coupled to one of said first and said second arms for selective application of an electrical signal to said one of said first and said second arms.

19. A nanophotonic switch as recited by claim 18, wherein said first and said second arms each include an arcuate section that changes the actual length of that arm without changing its virtual length.

20. A nanophotonic switch as recited by claim 19, wherein said arcuate section of said first and said second arms defines a bend radius ranging from approximately 20 micrometers to 100 micrometers.

21. A nanophotonic switch as recited by claim 20, wherein said arcuate section of said first and said second arms defines a bend radius ranging from approximately 50 micrometers to 100 micrometers.

22. A nanophotonic switch as recited by claim 18, wherein said virtual length of said first arm is approximately equal to said virtual length of said second arm.

23. A nanophotonic switch as recited by claim 22, wherein said actual length ranges from approximately 1 mm to approximately 4 mm and wherein said virtual length of said first and second arms ranges from approximately 100 to approximately 500 micrometers.

24. A nanophotonic switch as recited by claim 18, wherein each of said input coupler, said output coupler, and said interferometer arms comprises a photonic-well waveguide.

25. A nanophotonic switch as recited by claim 18, wherein each of said input coupler, said output coupler, and said interferometer arms comprises a photonic-wire waveguide.

26. A nanophotonic filter for receiving and filtering an optical signal, said filter comprising:

a Mach-Zehnder interferometer comprising:

an input coupler for receiving an optical signal;

an output coupler; and

first and second arms optically connected between said input and said output coupler along an optical path of said filter, said arms having respective first and second actual lengths and respective first and second virtual lengths extending along a direction of said interferometer, one of said first and said second arms having an actual length greater than its virtual length.

27. A nanophotonic filter as recited by claim 26, wherein said one of said first and said second arms includes an arcuate section that changes the actual length of that arm without changing its virtual length.

28. A nanophotonic filter as recited by claim 27, wherein said arcuate section defines a bend radius ranging from approximately 20 micrometers to 100 micrometers.

29. A nanophotonic filter as recited by claim 28, wherein said arcuate section defines a bend radius ranging from approximately 50 micrometers to 100 micrometers.

30. A nanophotonic filter as recited by claim 26, wherein said virtual length of said first arm is approximately equal to said virtual length of said second arm.

31. A nanophotonic filter as recited by claim 30, wherein said actual length of said first and said second arms ranges from approximately 0.25 mm to approximately 1 mm and wherein said virtual length of said one of said first and said second arms ranges from approximately 50 to approximately 250 micrometers.

32. A nanophotonic filter as recited by claim 26, wherein each of said input coupler, said output coupler, and said interferometer arms comprises a photonic-well waveguide.

33. A nanophotonic filter as recited by claim 26, wherein each of said input coupler, said output coupler, and said interferometer arms comprises a photonic-wire waveguide.

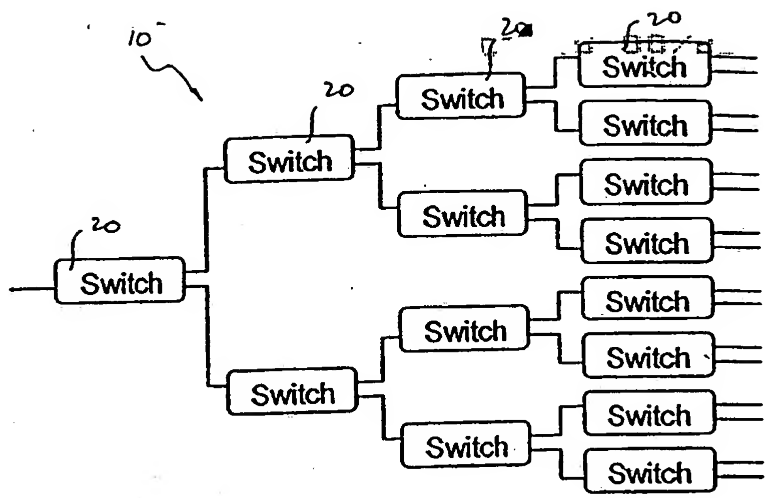

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FIG. 1

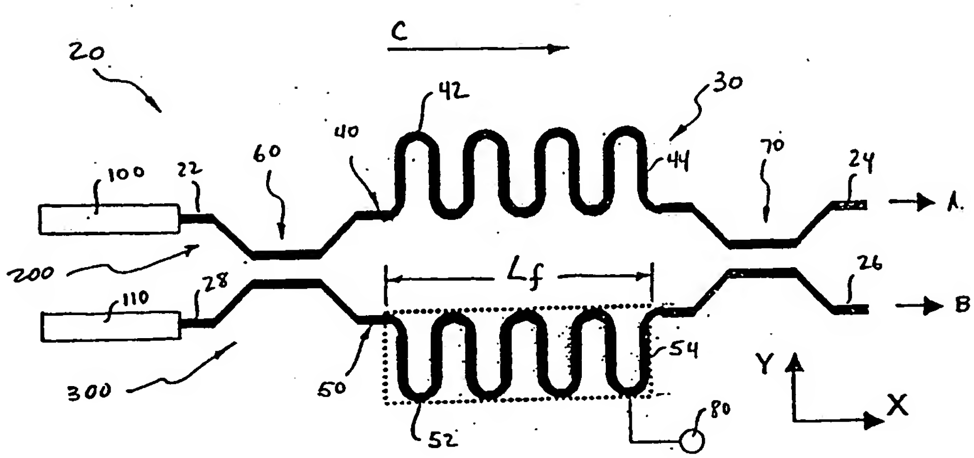
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FIG. 2

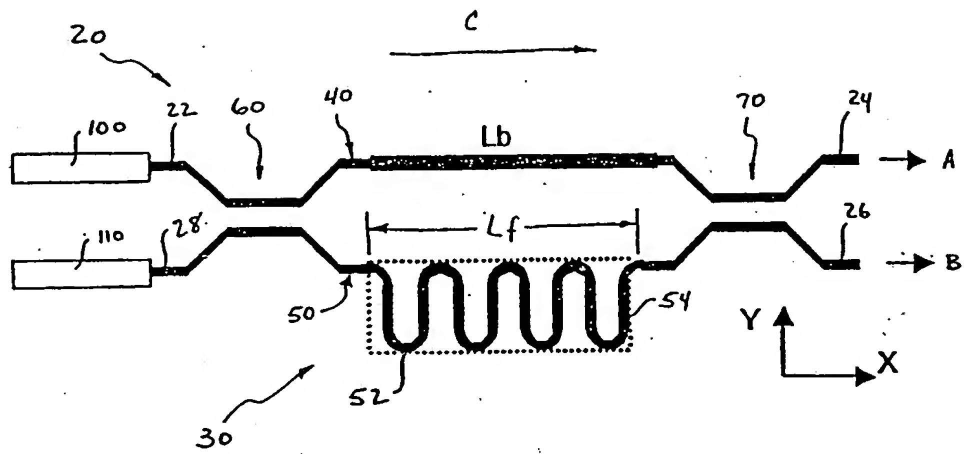
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FIG. 3

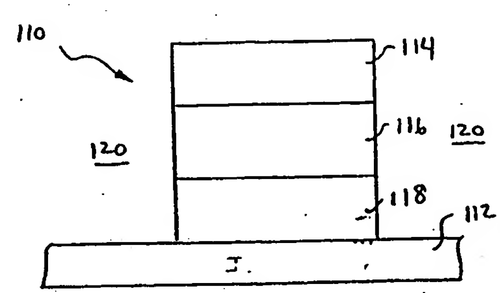
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FIG. 4